Large-Area and Cost-Effective Detectors for Neutrinos and Proton Decay

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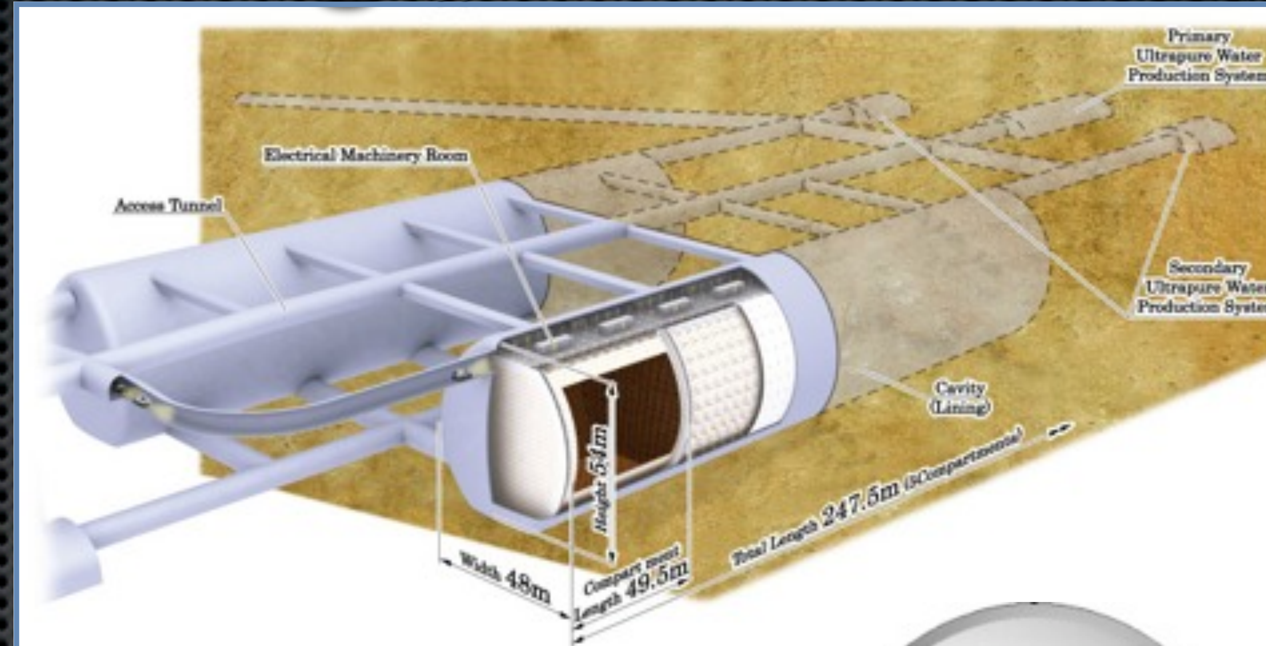
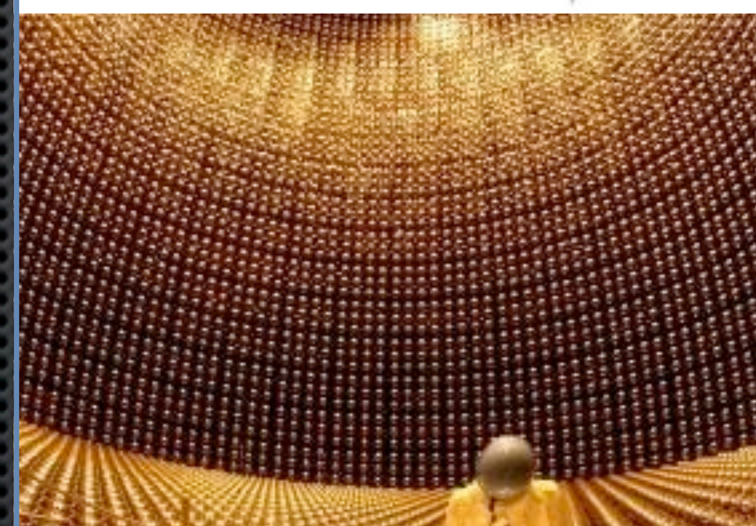
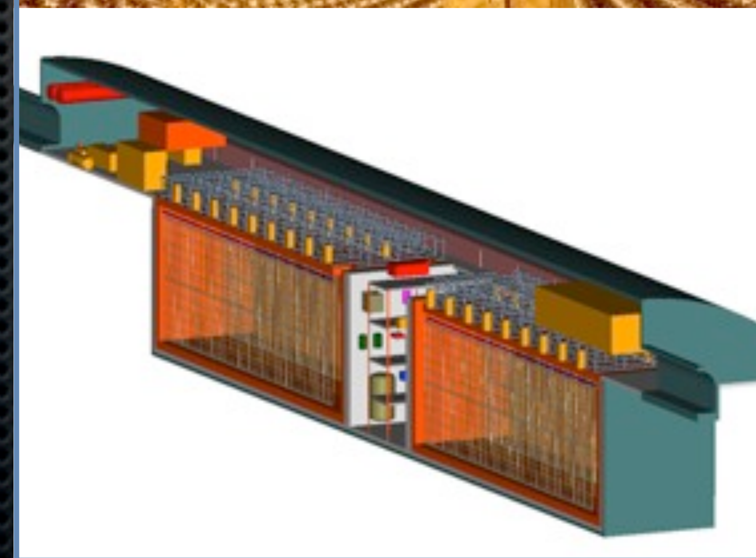
Next generation long-baseline

- The next generation of **neutrino experiments** will require massive detectors to reach the sensitivities needed to measure CP violation, the mass hierarchy, the θ_{23} octant and non-standard interactions.
(See P. Huber's talk)
- One or several **large detectors,** can provide the mass required to the next generation of long-baseline experiments.
- A challenge will be instrumenting the **very large surfaces/volumes**.
- A second challenge will be making **multi-purpose detectors** to enable a broader physics program.







The race for the next generation experiment

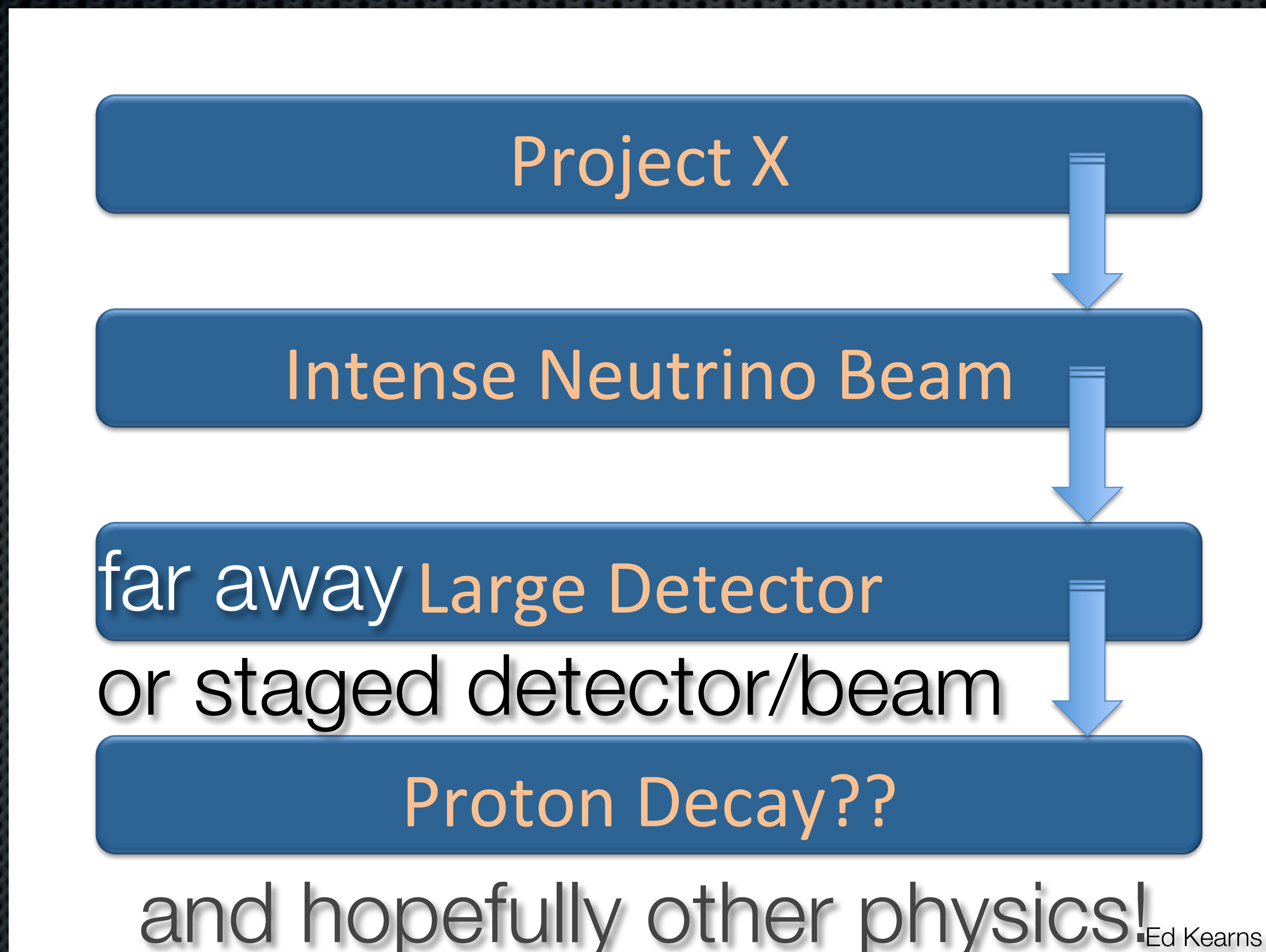
- What's on the table?

Hyper-Kamiokande	560 kton water cherenkov	99K PMTs (20% coverage)
LBNE	10/20/30 kton LAr TPC	surface/underground?
GLACIER/LBNO	20 kton LAr TPC	2-phase
LENA	51 kton liquid scintillator	30,000 PMTs

Ed Kearns

- A series of experiments are in their planning stages.
- All will attempt a broad range of physics in addition to studying long-baseline neutrino oscillations.
- Not discussing some other interesting options such as Pingu and INO.

Why project X and large detectors?



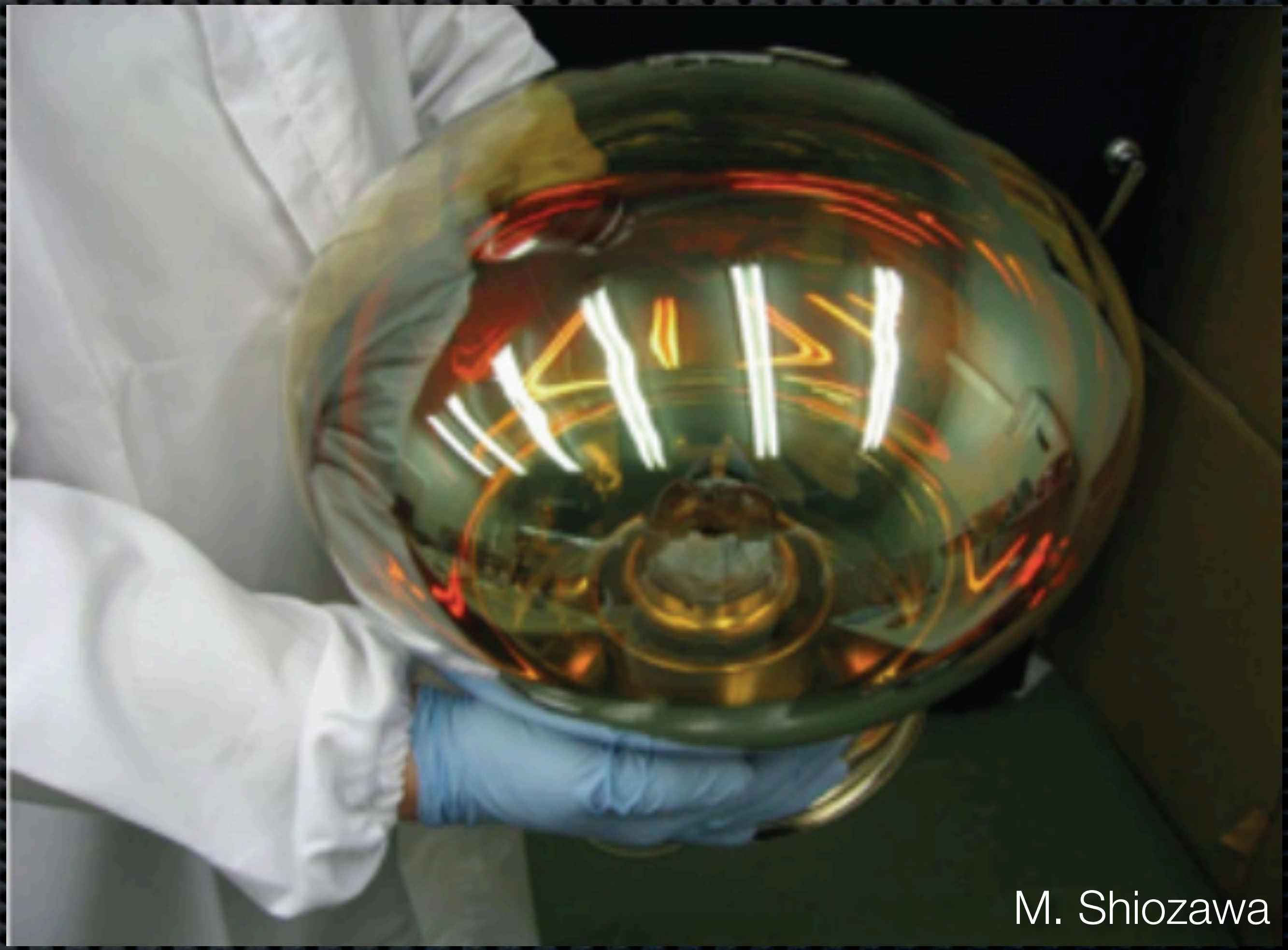
Next generation experiments

- Technology choices aside, the next generation of experiments require continued R&D on a portfolio of technologies.
- Planned experiments using very large detectors are already driving the development of these technologies.
- We have identified three main threads of development:
    - Photodetector R&D
    - Scintillator or other additives
    - Scintillation light collection and other improvements for LAr

Photodetector R&D

Building your detector within the next 5 years

- All 3 groups have considered photodetector technology in the market at this time.
- Collaborations working on characterization and design of **larger/cheaper/more efficient photosensors**.
- Working with Hamamatsu (sole manufacturer on most cases) on development of new options.

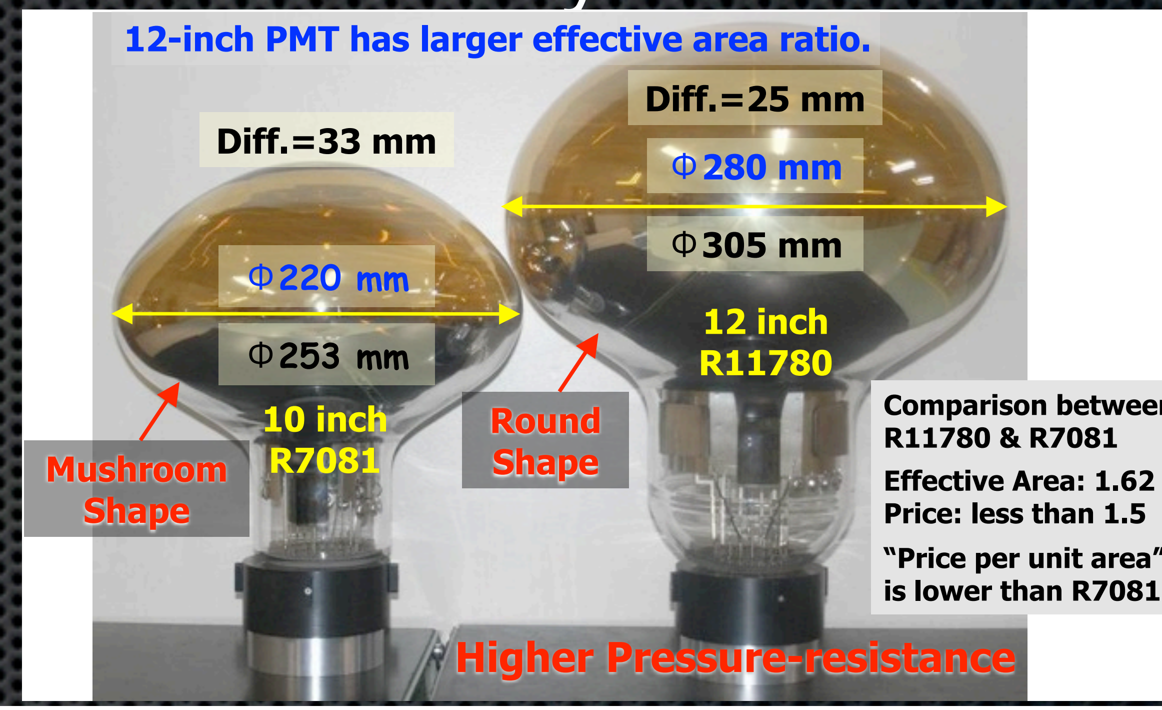


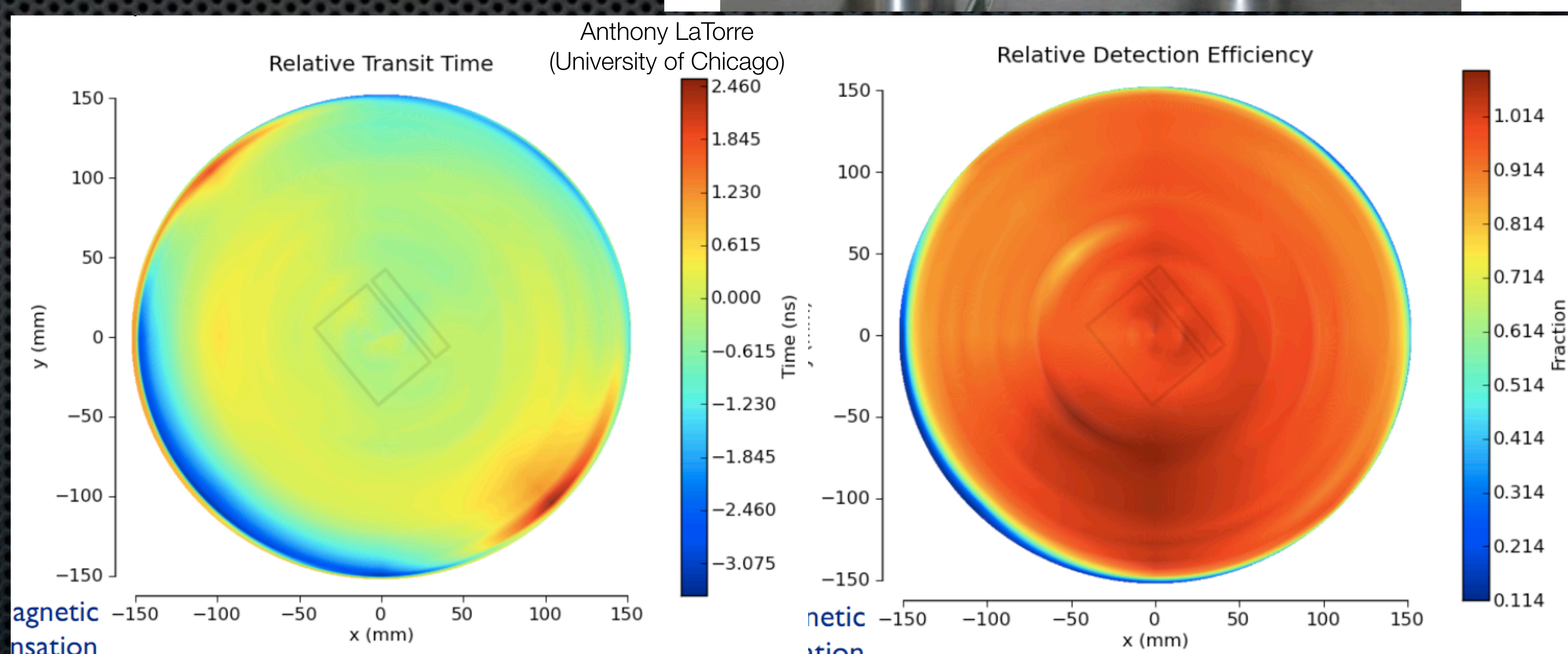
Talks on photodetector R&D by LBNE, HyperK, LENA

Photodetector R&D

Building your detector within the next 5 years

- 12-inch photomultiplier tubes were chosen for LBNE Water Cherenkov design and LENA.
- Detailed characterization work shows transit times varying by as much as 3ns.
  - Need different dynode structure
- QE 21 & 32% available.
- Work coming to a close, NIM paper to be written.



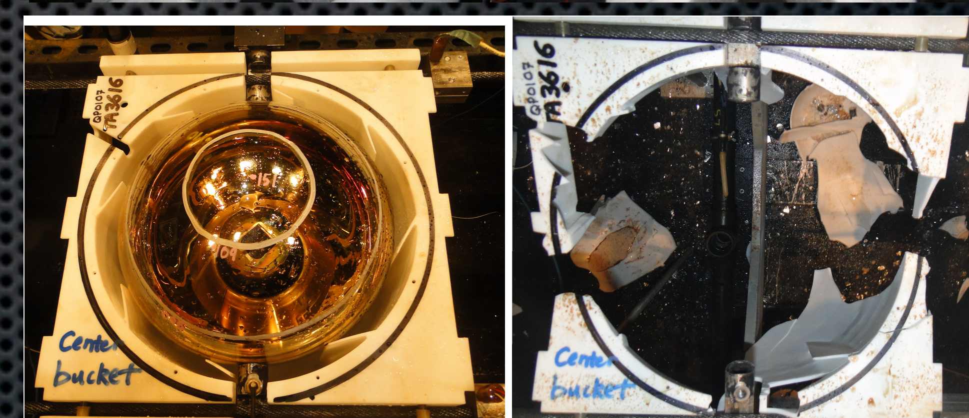


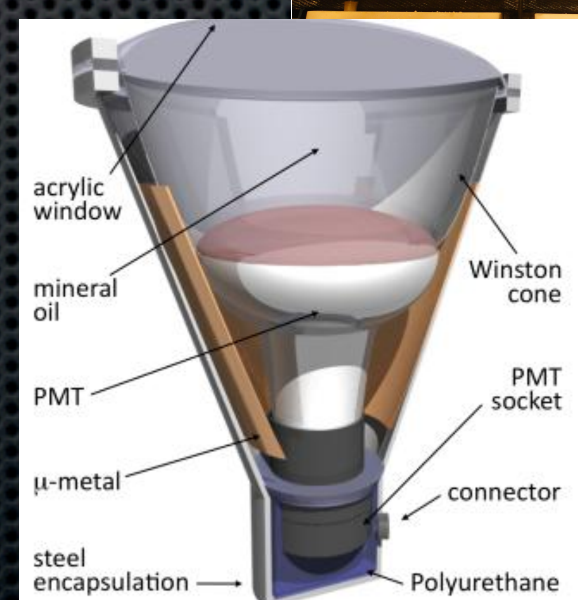
S. Perasso (Drexel)
J. Ling (BNL)
M. Tippman (TUM)

Photodetector R&D

Building your detector within the next 5 years

- Reduced number of phototubes requires additional light collection technologies:
  - Winston cones and Wavelength shifting plates
- Phototubes in large detectors are subject to high pressure environment.
  - Testing program has been completed at NUWC.
  - Up to 300 psi.
  - Designed housing.
- Other studies include glass R&D.
- **LENA undergoing similar process of characterization and design.**

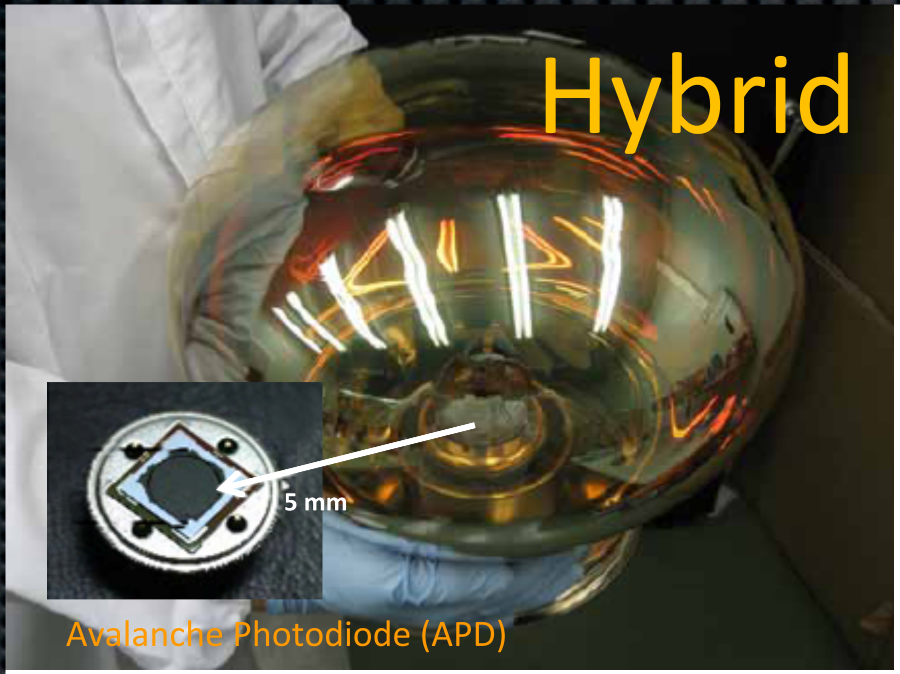


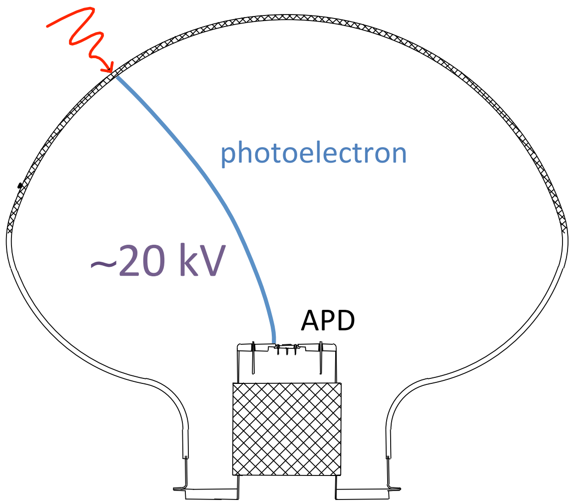


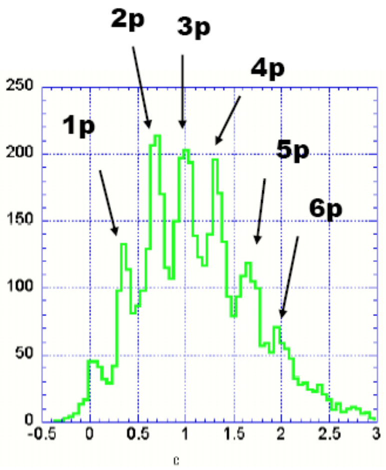
Photodetector R&D

Building your detector within the next 10 years

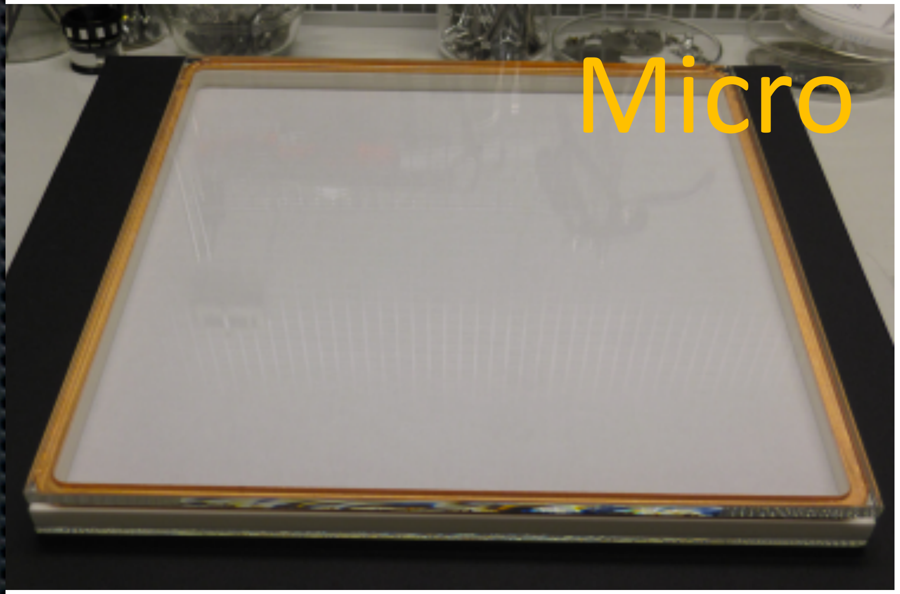
Hybrid Photo-Detector

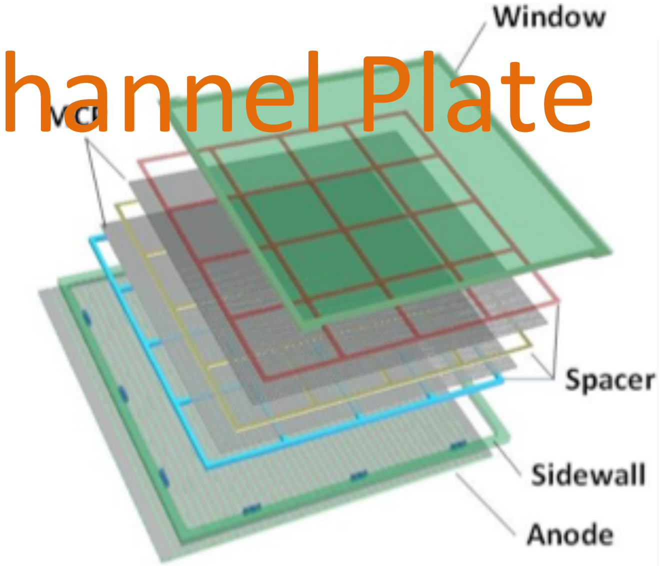






Micro Channel Plate





<100 ps timing

BUT…

Most important for Large Area Cost Effective Proton Decay Detectors: **COST** (and light collection)

M. Shiozawa

Photodetector R&D

Building your detector within the next 10 years

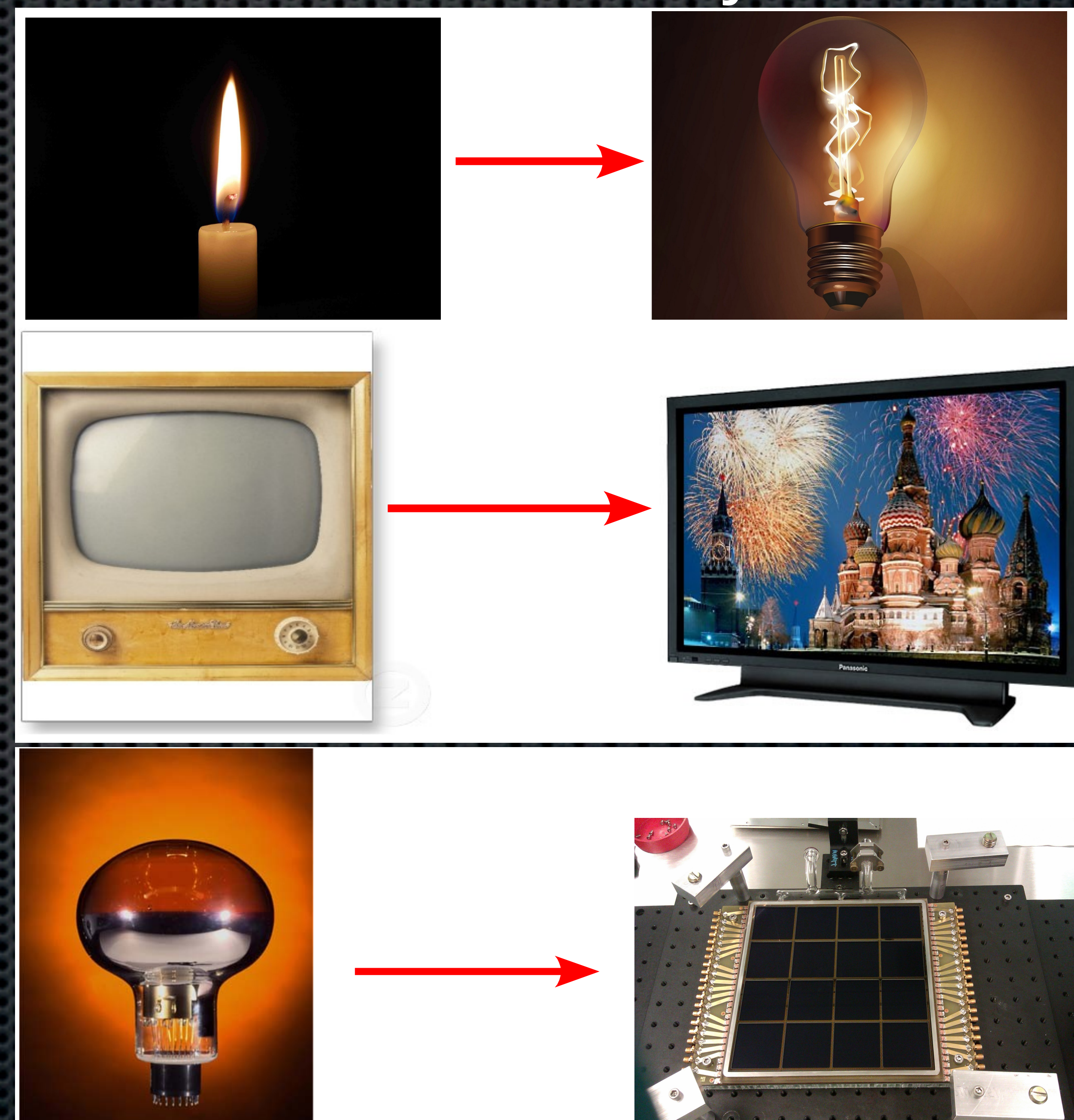
- Hyper-K planning to use 20-inch hybrid photodetector (HPD) or a 20-inch improved PMT.
- This summer they will be testing 8-inch HPD in water.
- 20-inch HPD prototype expected in ~1 year time.
- Expected production time for 99K photosensors is 4 years. The R&D time is about the same!

Photodetector

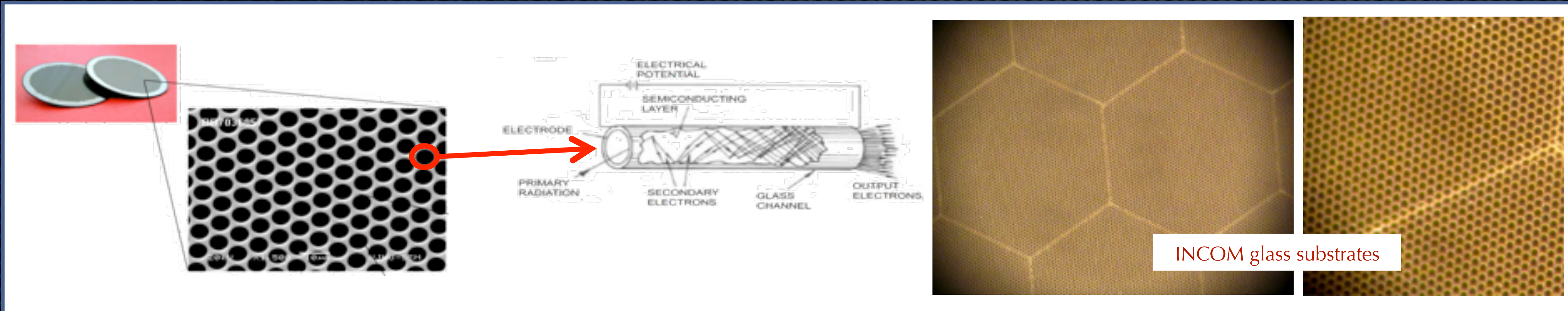
2012 R&D 100 50th ANNIVERSARY

Building your detector within the next 10 years

- **Large-area picosecond photodetectors** based on microchannel plates are being developed at Argonne National Laboratory in collaboration with other labs, universities and private companies.
- For this application, these could be tuned to:
  - Timing resolution of ~100 psec
  - Spatial resolution of ~1cm
- Alternatively, worse timing/less spatial resolution could be a lower price.



Large-area picosecond photo-detectors

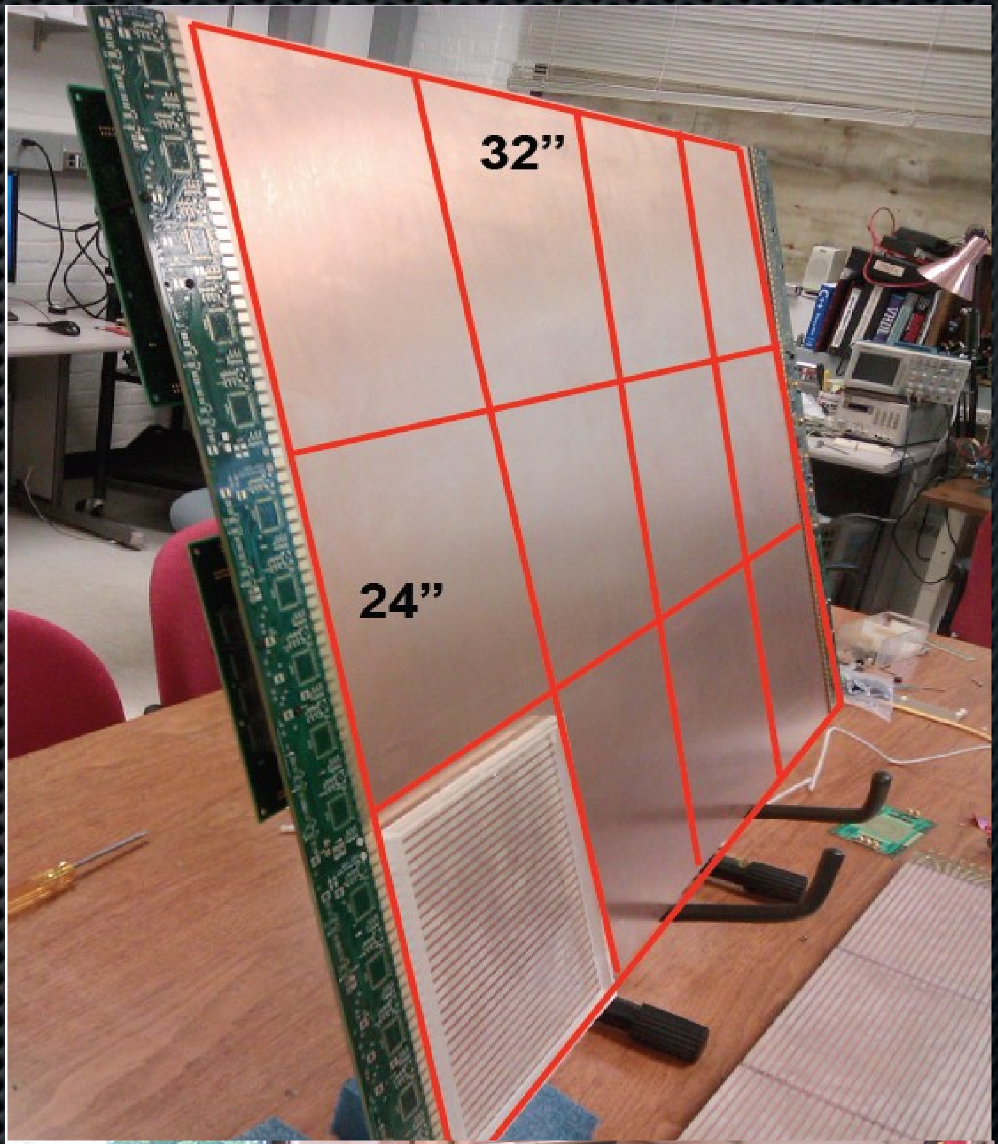


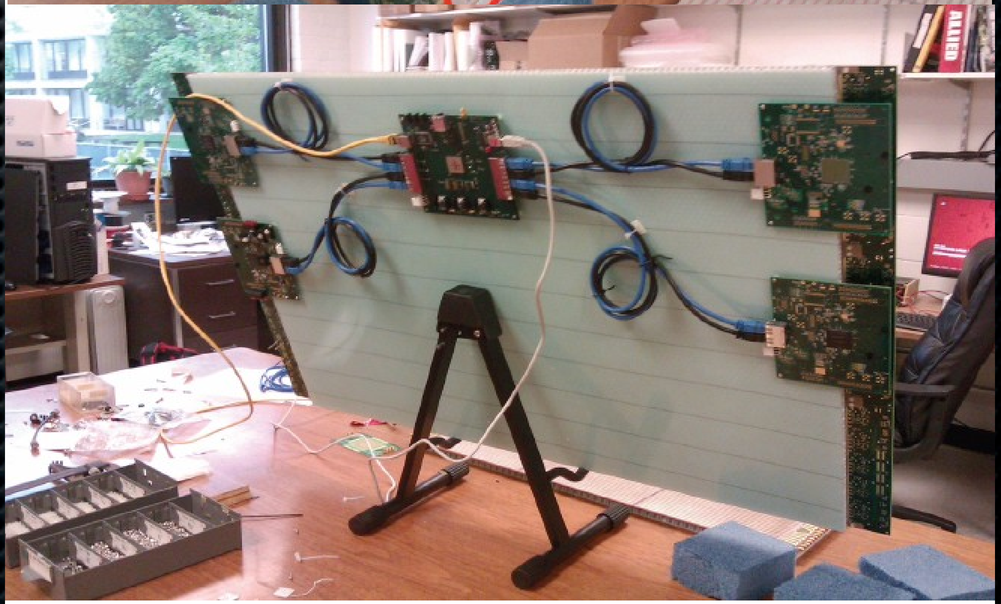
- Conventional MCP Fabrication:
  - Pore structure formed by drawing and slicing lead-glass fiber bundles. The glass also serves as the resistive material.
  - Chemical etching and heating in hydrogen to improve secondary emissive properties.
  - Expensive, requires long conditioning, and uses the same material for resistive and secondary emissive properties.
- Proposed approach for LAPPD:
  - Separate out the three functions: resistive, emissive and conductive coatings.
  - Handpick materials to optimize performance.
  - Use Atomic Layer Deposition (ALD), a cheap industrial batch method.

Approach demonstrated for 8-inch tiles

Large-area picosecond photo-detectors

- Microchannel plate photosensor in 8x8” tiles arranged in 24x16” super-module.
- Channel count optimized to large area/desired granularity.
- Integrated double-sided readout.
- Large-area flat panel provides robust construction. Low internal volume and use of known glass.
- No magnetic susceptibility.
- Scaled high QE photocathode.



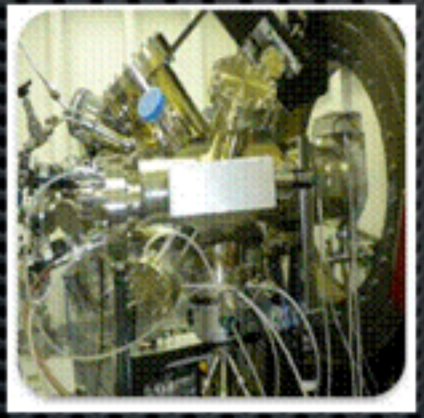


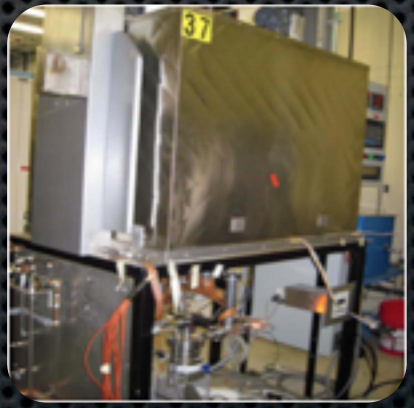
Progress shown in MCP plates, electronics, hermetic packaging

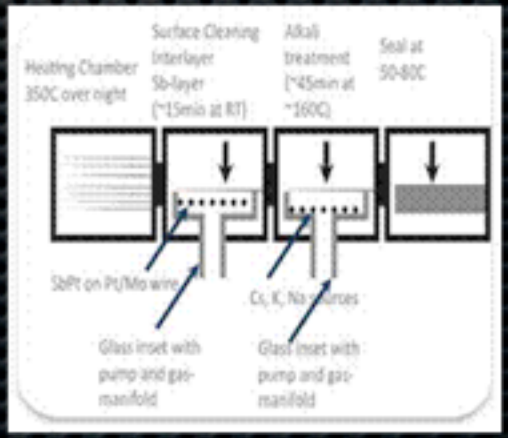
Photodetector R&D

Building your detector within the next 10 years

- A key challenge to large area photosensors continues to be photocathodes.
- High QE PMTs: SBA (35%) and UBA (43%) are only available in small format (< 4" diameter ?).
- Many fundamental detector properties such as dark current, quantum efficiency, response time, and lifetime are determined by the properties of the photocathode.
- The LAPPD collaboration has a program to study/develop photocathode technology.





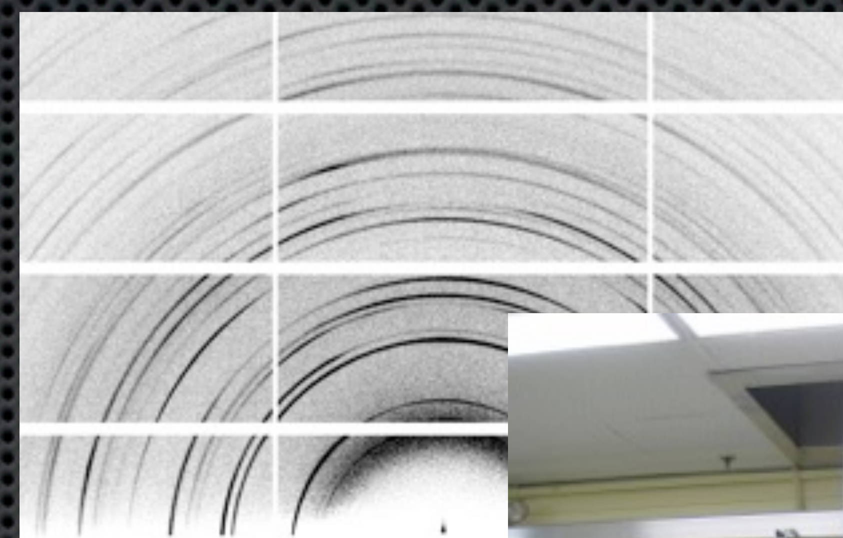


Microscopic Property ⟷ Macroscopic Property → Industrial Fabrication

Photodetector R&D

Building your detector within the next 10 years

- Photocathode R&D:
  - In-situ structural and chemical characterization.
  - Small photocathode growth process developed:
    - Oxygen discharge cleaning and oxidation;
    - Sb deposition monitoring via reflectivity measurement;
    - Bake out temperature, deposition temperature;
    - Control of alkali metals deposition.
  - QE as high as 24% has been produced and uniform within 15% without proper oxygen plasma cleaning and oxidation.

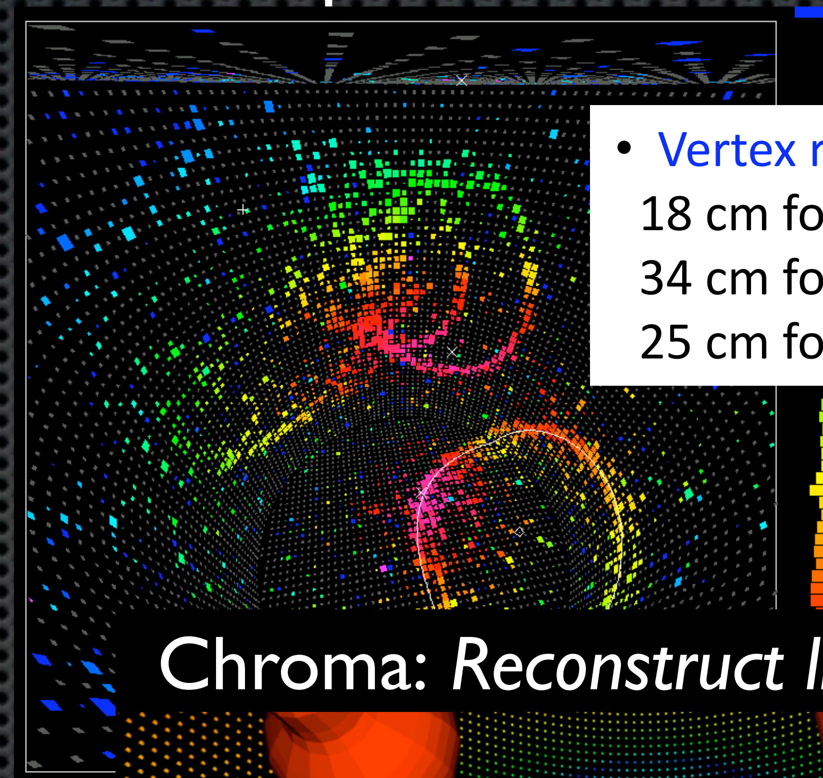


T. Junk (FNAL)
M. Wetstein (ANL)
S. Seibert (UPenn)

Other related R&D

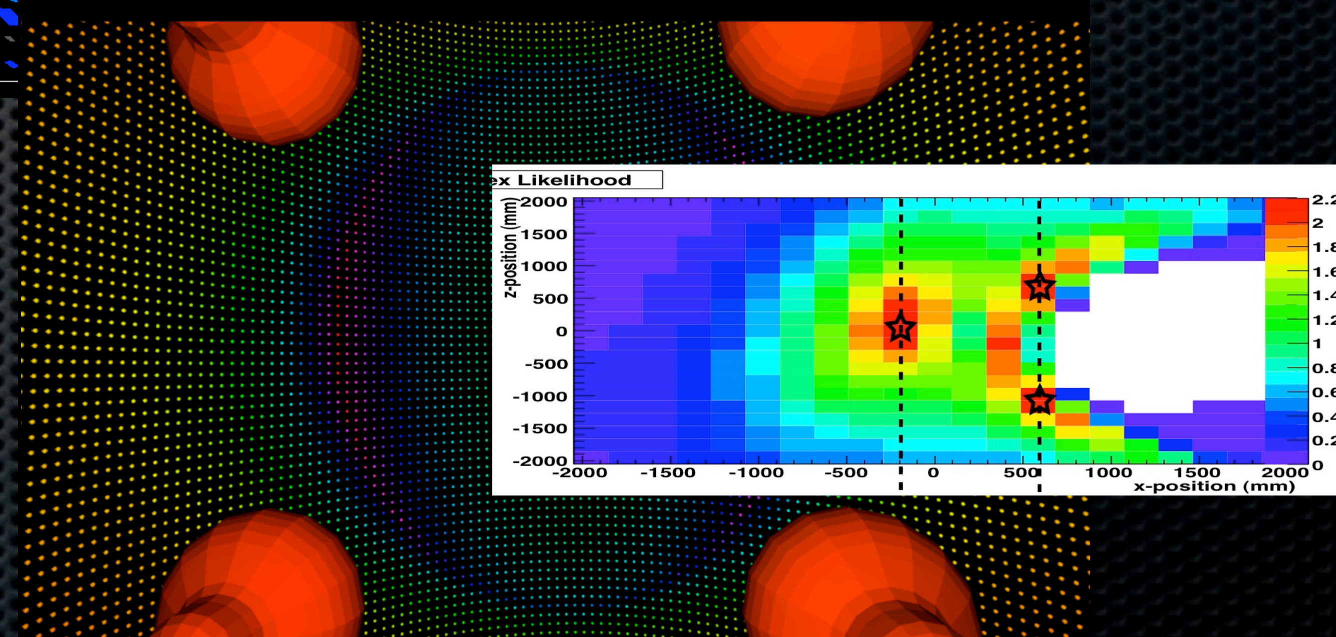
Reconstruction is important!

- Water Cherenkov detector mass is handicapped by a factor of 6.
- Several efforts underway to improve (mainly) WCh reconstruction.
- Use of more sophisticated algorithms (Miniboone), faster processing power (GPU), characteristics of faster photosensors.
- Changes in photosensor technology could impact the design of future large detectors.



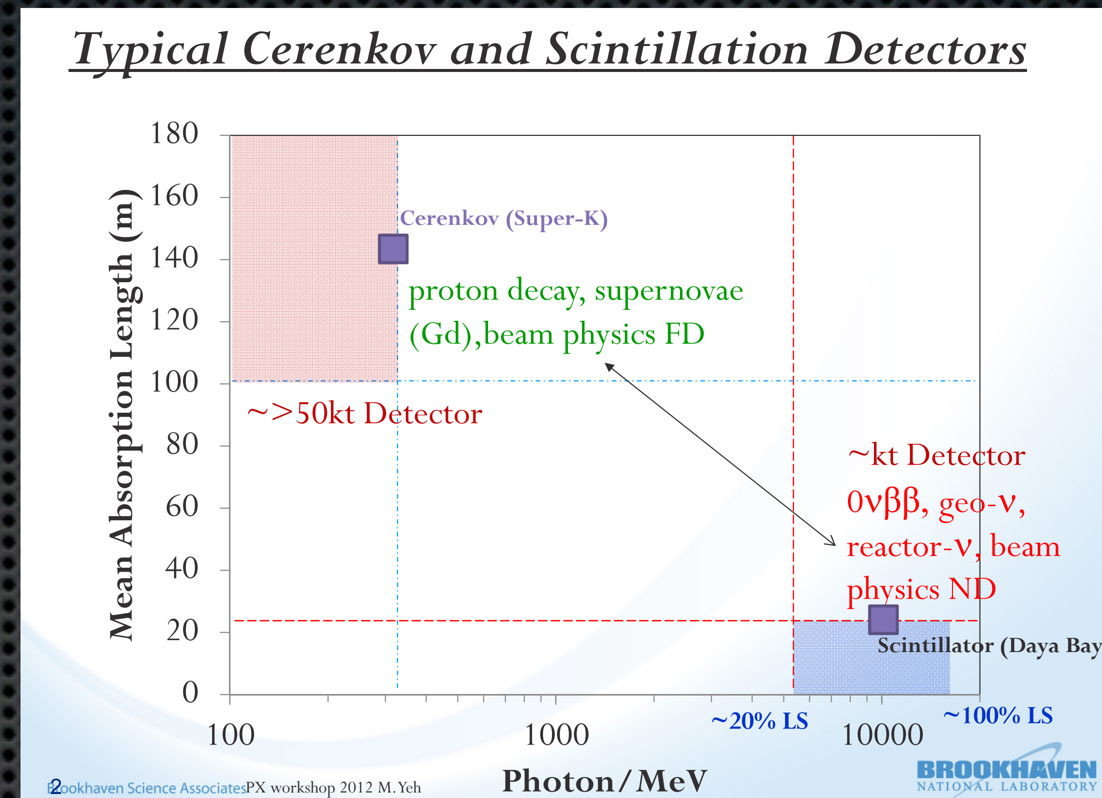
- Vertex resolution:
  18 cm for p→$e^+ \pi^0$.
  34 cm for single-ring electron events
  25 cm for single-ring muon events

Chroma: *Reconstruct like it's 2099*



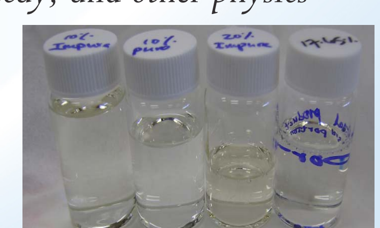
Scintillator and other additives

- Large liquid detectors can be enriched to improve their performance. Beyond using Cherenkov light alone as SuperK, scintillation light allows detection of particles below threshold.
- The program of R&D at BNL:
  - Investigation of a large variety of liquid scintillators
    - PC, PCH, DIN, PXE, LAB
  - Metal-loaded and water-based scintillators with high light-yield, long attenuation length and low flammability.
  - Capability of purifying and synthesizing materials in-house and of controlling the chemical processes.



Option-3: Water-based Liquid Scintillator

- *Cost-saving for larger detector (see talk in cost-effective detector session)*
- *Clean Cerenkov cone with scintillation at few hundreds of photons per MeV (tunable)*
- *Fast pulse and long attenuation length with minimum ES&H concerns*
- *A new technology ready to use:*
  - *Excellent detection medium for proton decay; and other physics*
  - *Easy to be handled for large detector*
  - *Gd-soluable*
  - *A economic large veto solvent*



Scintillator and other additives

Sensitivity of WbLS for PDK+

- ***Event Signal-like:***

  Prompt
  - K^+ scintillation

  Delay
  - π^+ and μ^+ scintillation
  - π^0 scintillation
  - Cerenkov rings from μ^+, π^+, π^0, Michel electron, etc.
- ***Event Selection Rules***
  - 12.8 ns between prompt and delay.
  - No ring in Prompt.
  - Energy Cut on prompt event.
  - Rings in delay
  - Energy cuts in delay with rings
  - etc…
- *Compare to SK (170 events in 1489 days), the 3-fold coincidence cuts down to ~5/y; PSD/Michel position cut can further suppress the bkg. event to 0.25/y.*
- *10-yr run could reach a sensitivity of 10^{34} for the PDK$^+$ mode).*

M. Yeh (BNL)
M. Vagins (IPMU)

Scintillator and other additives

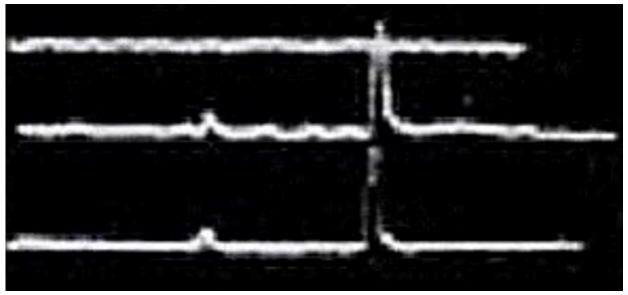
- Adding Gd to water or water soluble scintillator enables observing neutron capture.
- It enables:
- Full de-convolution of a galactic supernova's ν signals
- Early warning of an approaching SN ν burst
- Proton decay background reduction (5X)
- New long-baseline flux normalization (T2K/Project X)
- Matter- vs. antimatter-enhanced atmospheric ν samples

Inverse Beta Decay Detection with Gd

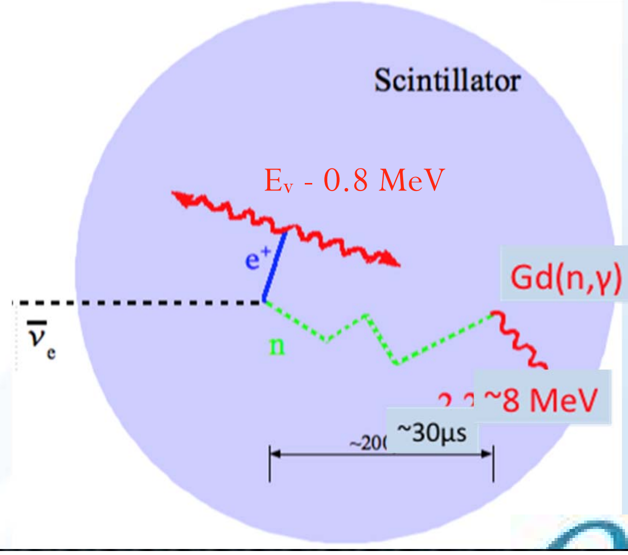
- $E_{threshold} = 1.8$ MeV
- 'Large' cross section $\sigma \sim 10^{-42}$ cm^2
- Distinctive coincidence signature in a large liquid scintillator detector

$$\bar{\nu}_e + p \to \boxed{e^+} + n$$

$$\mathrm{n} + {}^{A}\mathrm{Gd} \to {}^{A+1}\mathrm{Gd} + \boxed{\gamma' s}$$



Cowan & Reines, Savannah River 1956



Background events for $p \to e^+\pi^0$ (4.5Megaton years)

	ν interactions	secondary interactions in water
1	$\nu n \to e^- p \pi^0$	Neutron production by the proton
2	$\nu p \to e^- p \pi^+$	Neutron by π^+
3	$\nu p \to e^- p (\pi^+) \pi^0$	
4	$\nu n \to \nu p \pi^- \pi^0$	
5	$\nu n \to e^- p$	Neutron by the proton
6	$\nu n \to e^- n \pi^+ \pi^-$	
7	$\nu p \to e^- p (\pi^+) \pi^0$	
8	$\nu p \to \nu p \rho$	
9	$\nu O \to e^- O \pi^+$	Neutron by π^+
10	$\nu n \to n \rho$	neutron and π^- by the neutron

M. Shiozawa NNN09

- high energy neutrino events are accompanied by n
- assume proton decay is not accompanied by n
  - * surely not for free proton
  - * also not for γ-tag states
- consider Gd addition to WC to increase n-capture tag efficiency
- Gadolinium R&D underway at SK

Liquid Argon R&D

Building your detector within the next 5-10 years

Main Lines of Development

- ✓ [LAr Purity (materials' compatibility & selection) and LAr Purification]
- Ionization Charge signal extraction: alternatives to wires
- Scintillation Light signal extraction *(the most promising line of development)*
- Electron Charge Drift over long distance
- Cryostat Insulation schemes and developments
- Cold read-out electronics vs. Warm electronics
- Event Reconstruction and Off-line code developments

F. Cavanna

Liquid Argon R&D

Building your detector within the next 5 years

- The following are outstanding questions on LArTPC performance
  - EM shower energy resolution
  - Hadronic shower energy resolution, visible vs invisible energy
  - E_{had}/E_{EM} ratio
  - Directionality of through going particles using delta rays
  - Particle identification
  - dE/dx for several particle species
  - Light collection efficiency
  - Surface operation in a high cosmic ray rate environment
  - Studies of proton decay backgrounds
  - Diffusion studies over long drift distances

Liquid Argon R&D

Photon Detection Overview

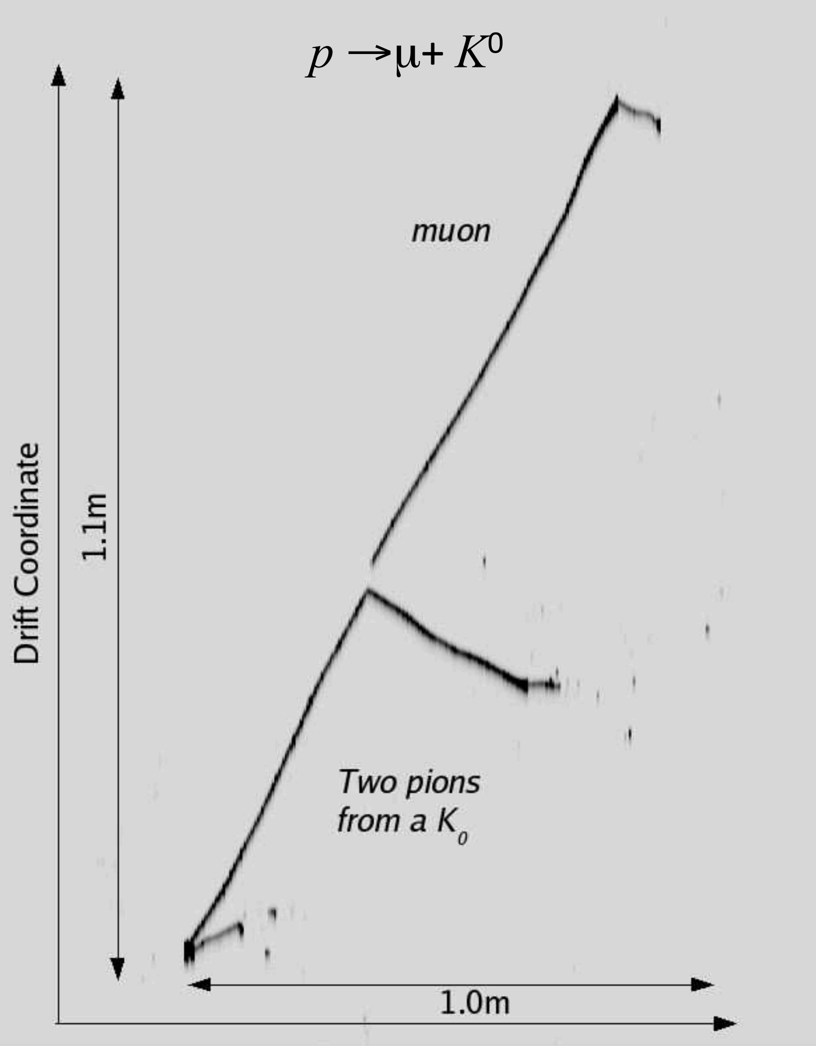
2 processes production scintillation light in LAr

$$\mathrm{Ar}^* + \mathrm{Ar} \rightarrow \mathrm{Ar}_2^* \rightarrow 2\mathrm{Ar} + \gamma$$

$$\mathrm{Ar}^+ + \mathrm{Ar} \rightarrow \mathrm{Ar}_2^+ + e \rightarrow \mathrm{Ar}_2^* \rightarrow 2\mathrm{Ar} + \gamma$$

prompt light at 6 ns (23%) and late light at 1.6 μs (77%)

photons emitted in VUV at 128 nm where detection is difficult



- If the detector is underground, detecting scintillation light will enable a wide variety of topics by providing a trigger:
  - Proton decay, supernova neutrinos, atmospheric neutrinos, mitigation of spallation backgrounds.

Liquid Argon R&D

Building your detector within the next 5 years

Photon detection is a valuable tool in a large surface LAr detector for mitigating backgrounds from CRs

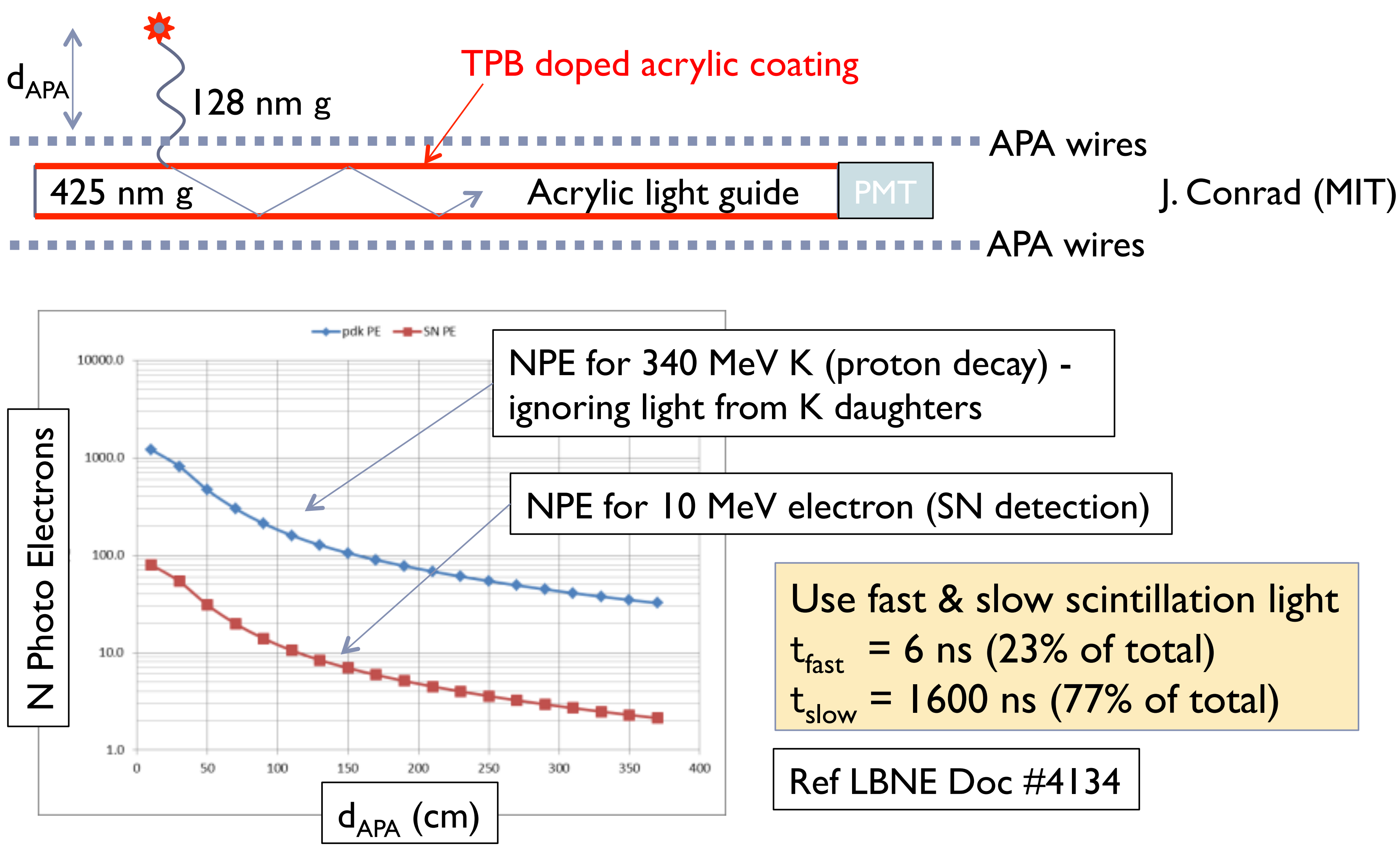
- beam spills ~ few μsec, drift times ~ few msec
- the CR background rate ~ 10 kHz
- in a few msec, a handful of CR muons will fall within the drift time window
- with accurate t_0 from the photon detection system, events outside the beam spill window can be accurately identified; with dE/dx corrected with t_0, particle ID will further improve background rejection
- in conjunction with tracking that point events back to Fermilab, photon detection improves beam neutrino detection

Liquid Argon R&D

Building your detector within the next 5 years

Photon Detection

Stuart Mufson

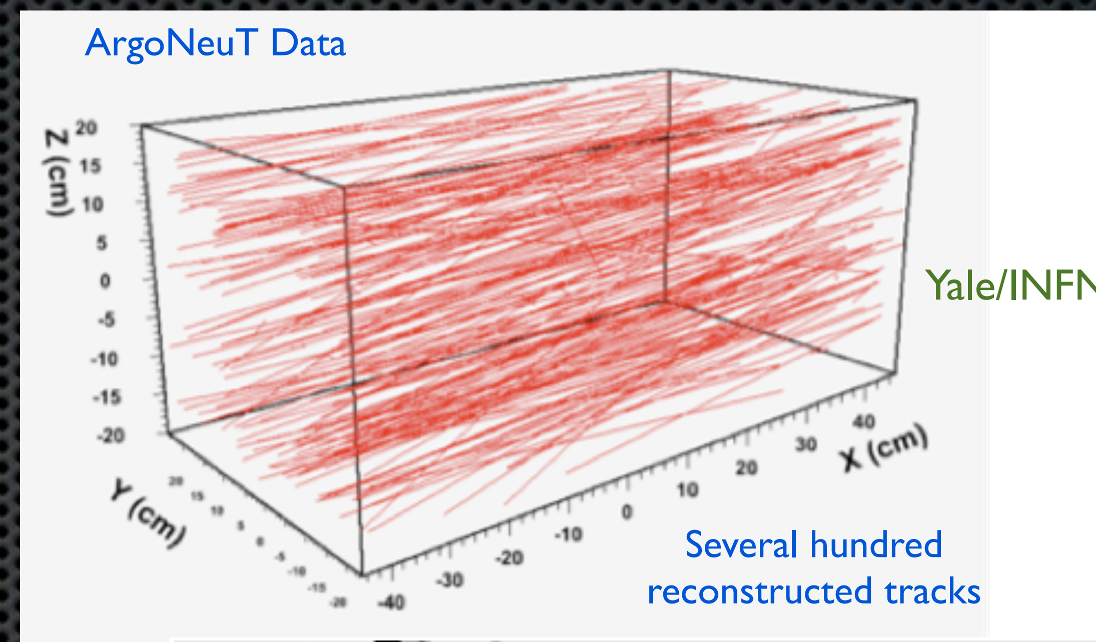


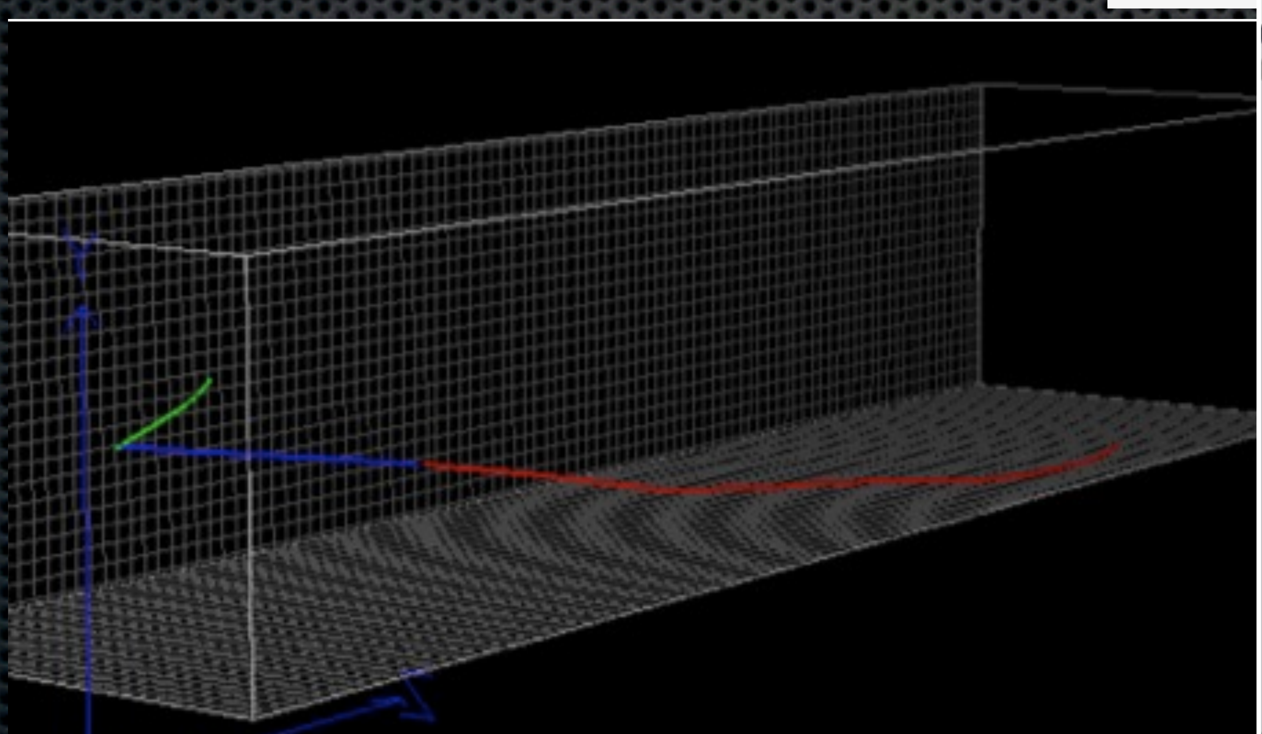
B. Rebel (FNAL)
M. Kirby (FNAL)

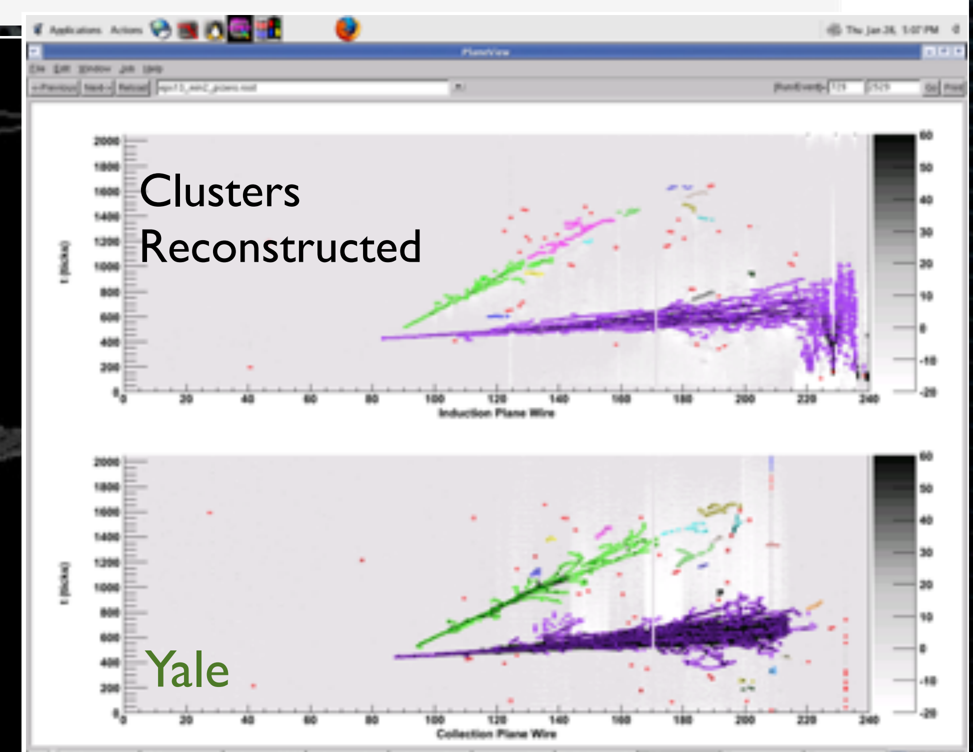
Other related R&D

Reconstruction is important!

- Reconstruction making significant progress.
- Variety of approaches in the works.
- Looking forward to studies beyond hand scanning.
- Specific questions of interest to proton decay have been asked.
- Realistic numbers 6 months away.







Conclusions

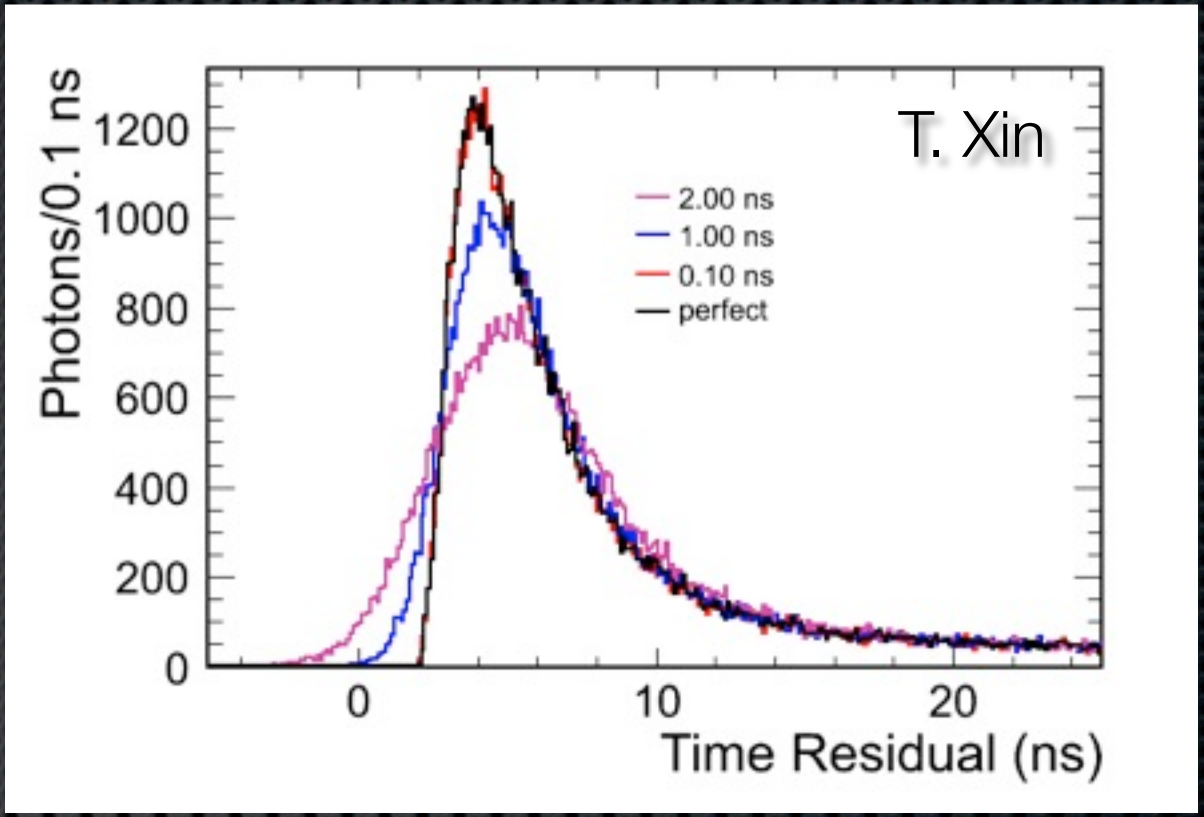
- Most of the studies for water Cherenkov in the US are coming to a close. Hyper-K and Lena are evaluating photodetector technology.
- A new generation of larger area photodetectors is in development.
  - Enabling new capabilities in experiments and driving the cost down of key elements such as photocathodes.
- Large liquid detectors are likely to be built. New additives to water might make Cherenkov+scintillation interesting for an even wider physics program.
- Liquid Argon R&D is in progress. It is possible that light collection technology is required to build the detector on the surface.
  - Alternatives should/will be explored not just for light collection.

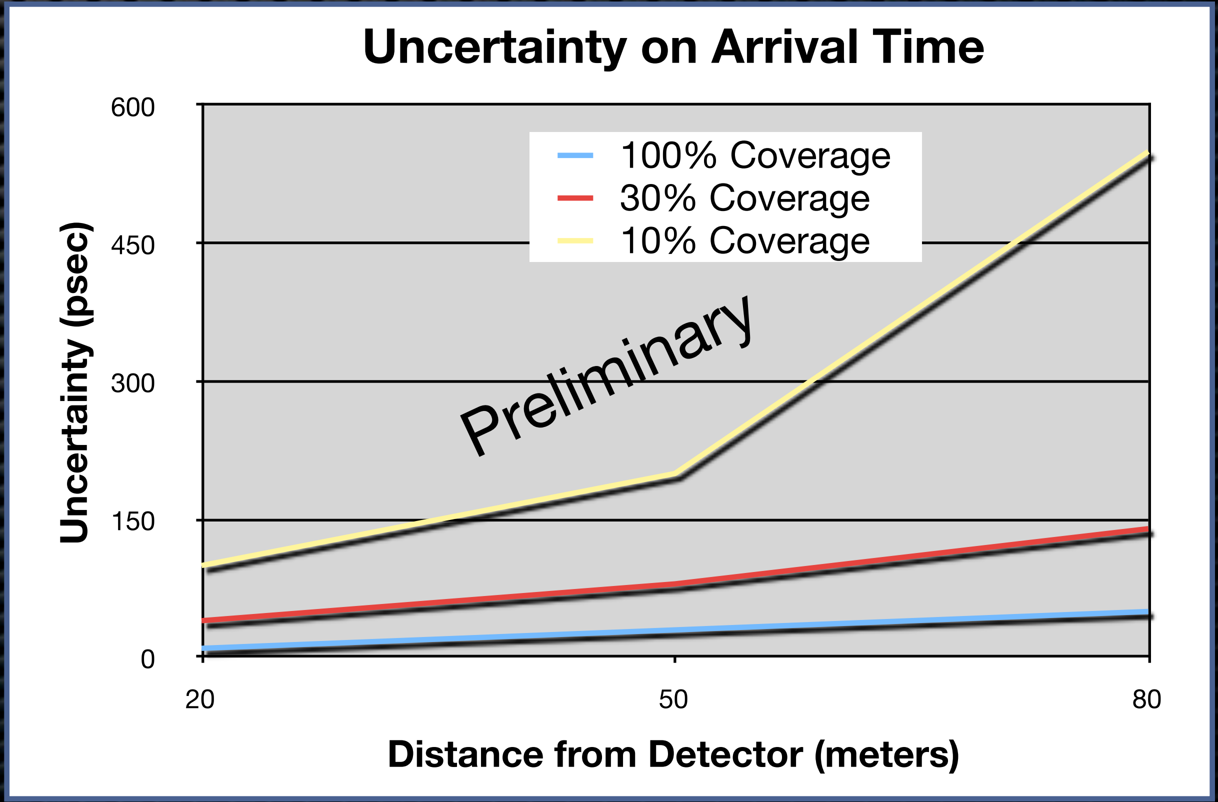
A diverse portfolio of large-area technologies will enable a strong Project X program

Backup

Next generation Long-Baseline

- **Large-area fast photodetectors** based on microchannel plates are being developed at Argonne National Laboratory:
  - Timing resolution of ~100 psec
  - Spatial resolution of ~1cm
- The application of this new technology could enhance background rejection and vertex resolution by **improving spatial and timing information**.
- We have shown that for a given detector size, the uncertainties in the position of the leading edge become smaller if larger photodetector coverage is considered.
- Work in progress developing simulations and reconstruction in less ideal cases.

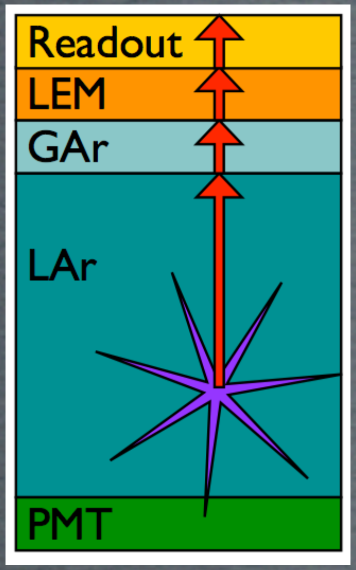




M. Sanchez (ISU/ANL), M. Wetstein (U Chicago/ANL),
I. Anghel (ISU), G. Davies (ISU), T. Xin (ISU)

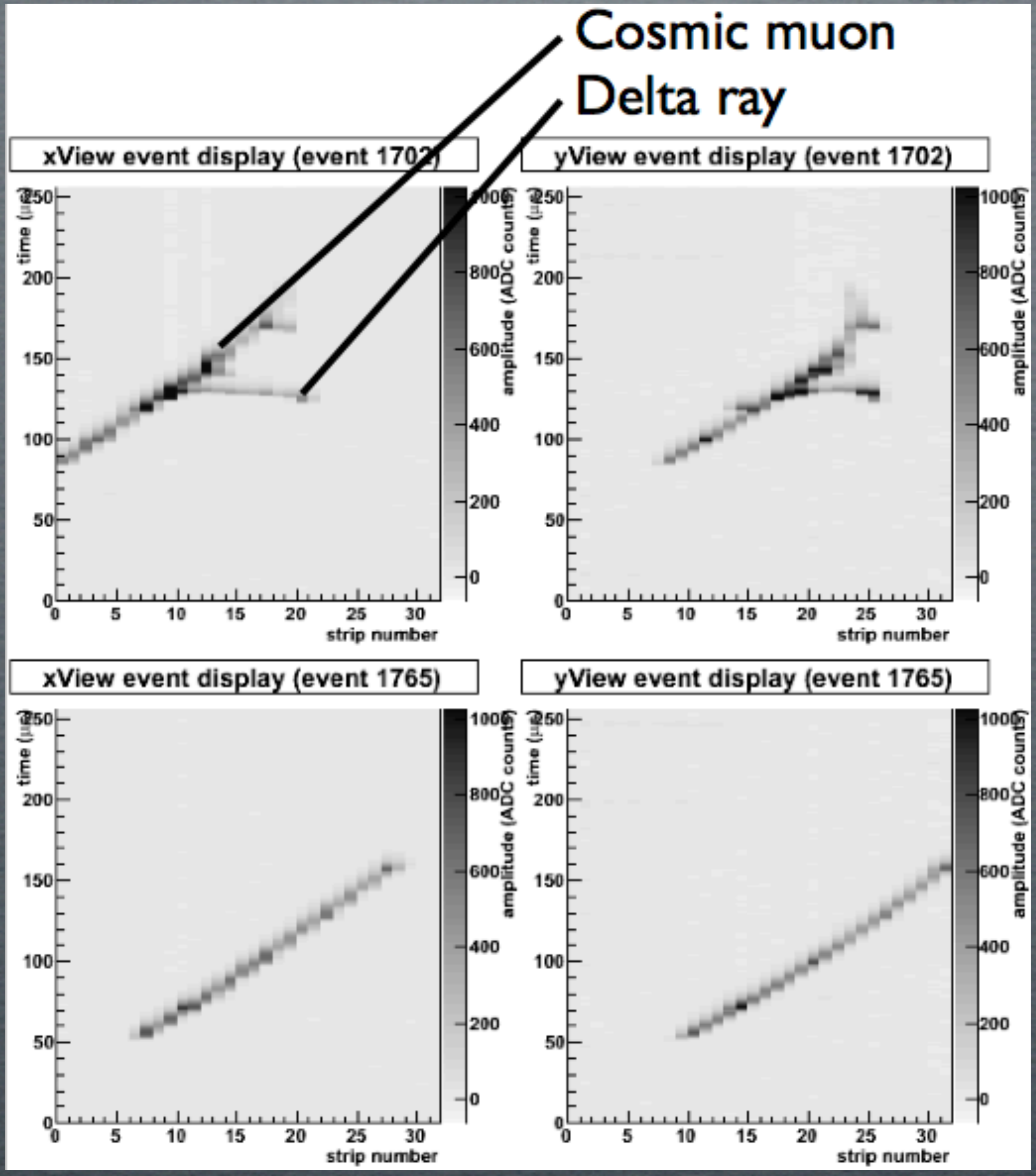
Project funded under NSF CAREER

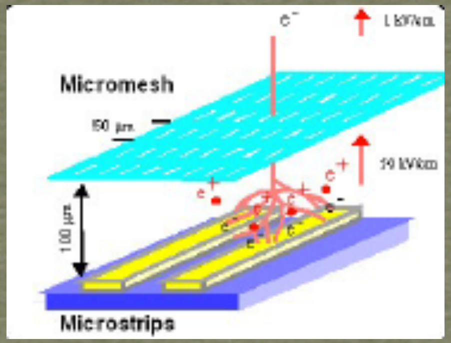
LAr LEM-TPC @ CERN (ETH)



from concept to real detector

• LEM: Double phase Argon Large Electron Multiplier TPC concept provides a 3D-tracking and calorimetric device capable of adjustable charge amplification.





• MM: MicroMega concept under study @ CEA-Saclay ⊕ ETH

• It is a promising readout technology for next generation ν-detectors (fine spatial resolution, large active area and gain of the order of 10) and for Dark Matter detectors

1. Proton Decay

- critical issue is to achieve extremely high rejection of backgrounds, less than one event per 100 kt-yrs, that could masquerade as the very rare signal.
  - "golden" proton-decay channel in LAr (p -> $K^+\nu$) mimiced when a K^+ outside the exterior cathode planes enters the fiducial volume
  - photon detection unambiguously determines the position of the event in the detector

2. Supernova Neutrino Bursts

- detailed timing information from a photon system greatly enhances the understanding of the evolution of catastrophic stellar core collapse processes

3. Atmospheric Neutrinos

- unique among sources used to study oscillations since the oscillated flux contains neutrinos and anti-neutrinos of all flavors, thereby enabling sensitive searches for new physics signatures
- the photon detection system improves the energy resolution, reducing systematic errors in the analyses, enabling more accurate searches

4. Mitigation of Spallation Backgrounds

- muons and muon-induced fast neutrons entering the detector from the surrounding rock
- backgrounds are important for neutrino detection in the range of a few to a few tens of MeV

Proton decay modes

	Mode	Super-K Water Ch. Efficiency	BG Rate (/Mt y)	LAr (generic) Efficiency	BG Rate (/Mt y)
B-L	$e^+\pi^0$	45%	2	45%	1
	$\nu\ K^+$	16%	7	**97%**	**1**
	$\mu+\ K^0$	10%	5-10	**47%**	**<2**
B+L	$\mu^-\ \pi^+\ K^+$	?	?	**97%**	**1**
	$e^-\ K^+$	10%	3	**96%**	**<2**
$\Delta B=2$	n nbar	12%	260	**?**	**?**
		Rough and unofficial SK efficiency & BG - ETK		A. Bueno et al. hep-ph/0701101	